INVESTIGATION OF RTP AND BELT FIRED SCREEN PRINTED AL-BSF ON TEXTURED AND PLANAR BACK SURFACES OF SILICON SOLAR CELLS

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ABSTRACT

Quality of screen printed (SP) Al-BSF on textured and planar back surfaces was assessed by fabricating and analyzing Si solar cells. BSF was formed by firing SP-Al in a conventional belt furnace as well as in an RTP system. I-V and IQE measurements revealed that the BSF formed on a textured surface by belt firing had the poorest quality. Belt BSF on the planar back resulted in 15 mV higher V_{oc}. In contrast to the belt BSF, RTP BSF was superior and showed very small difference (≤ 5 mV) between the flat and textured back cells. The positive effect of RTP is attributed to much higher temperature ramp-up rate which produces uniform Al melting and reduces the influence of surface condition. In contrast, slow ramp-up in belt produces non-uniform BSF even on a planar surface. This effect gets worse on textured surfaces.

1. INTRODUCTION

Texturing is an important feature for solar cells which can give rise to more than 1% increase in absolute efficiency [1]. The most widely used method for texturing is the alkaline etching, which forms regular pyramids on (100) oriented crystalline silicon. This technique is typically implemented in industry without protecting the back surface and, therefore, creates a textured surface on both sides of the solar cells. An Al back surface field (BSF) is usually formed at the rear surface of the cells by screen-printing of Al followed by Al-Si alloying. It has been shown that Al-BSF is quite effective on planar surfaces [2]. However, the impact of the texture on the quality of screen-printed Al-BSF has never been quantified. Therefore in this paper, we investigated the quality of the screen-printed Al-BSF on the textured surface. Complete solar cells were fabricated with textured and planar back surfaces. The BSF quality was evaluated by analysis of the measured long wavelength Internal Quantum Efficiency (IQE) and cross-section Scanning Electron Microscopy (SEM). In addition, Al-BSF was formed in two types of furnaces: a commercial belt furnace and an RTP (rapid thermal processing) system. In the case of RTP, temperature ramp-up rate was varied systematically and the cells were analyzed to quantify its impact. Belt and RTP BSF on textured and planar surfaces were analyzed and compared.

2. EXPERIMENTAL

In order to enhance the impact of BSF on cell performance, boron-doped CZ silicon wafers with resistivity of about 4-5 ohm-cm were used for cell fabrication. High resistivity wafers were used to enhance the sensitivity of BSF quality on V_{oc}. After the alkaline texturing on both sides, 45 Ω/square n-type diffusion was performed followed by SiN_x deposition on the front as an Anti-Reflection Coating (ARC). In order to prepare planar back surface samples with textured front, 30% KOH solution heated to 90°C was used to etch away the textured structure only on the back side using SiN_x coating on the front as a protection mask. To ensure that KOH etching does not affect the nitride's antireflection property, surface reflection was measured before and after etching which showed negligible change. All the wafers were then subjected to the Al screen-printing process. Two different furnaces were used to fire the Al-BSF: i) RTP furnace and ii) belt furnace. In both cases, the peak temperature was set to 850°C with alloying time of ~2 minutes. Front contacts were formed on all the samples by Ag screen printing and firing in the belt furnace, followed by a forming gas anneal. Finished cells were analyzed by I-V characteristic. The quality of the BSF was assessed by the IQE response in the long wavelength range. The 700-940 nm range is of most interest for IQE because it is quite sensitive to lifetime and back surface recombination velocity (BSRV) for the 200-300 μm thick samples, with negligible effect from any small difference in back surface reflectance. The lifetimes are expected to be the same for all the wafers since they are from the same section of the ingot and were subjected to identical processing. Additionally, cross-section SEM pictures of Al-BSF were taken and compared. Prior to SEM measurements, the samples were broken along the crystal direction followed by etching in 1:3:6-HF:HNO_3:CH_3COOH for 10 s. The purpose of this etching is to delineate the Al-BSF (heavily p-doped) from the bulk (lightly p-doped) region [3]. All the SEM pictures were taken perpendicular to the cross-section area of the cut wafers.

In the beginning of the study, the ramp-up rate for the Al-BSF firing in the belt furnace and RTP furnace was set to 20°C/s and 100°C/s, respectively. Initial cell analysis showed some difference in the Al-BSF quality due to the difference in ramp-up rate in the two furnaces. Therefore, subsequent experiments were conducted by varying the ramp-up rate in RTP in the range of 20°C/s to 100°C/s while keeping the same ramp-up rate (20°C/s) in the belt furnace.

3. RESULTS AND DISCUSSION

Fig. 1 shows the open circuit voltage (V_{oc}) of RTP and belt BSF cells with the textured and planar back surfaces. Note that the ramp-up rate in the belt and RTP furnaces were 20°C/s and 100°C/s, respectively. A very significant difference of ~15 mV in V_{oc} was observed between the cells with textured and planar back when the Al-BSF was formed by firing in the belt furnace. However, BSF firing

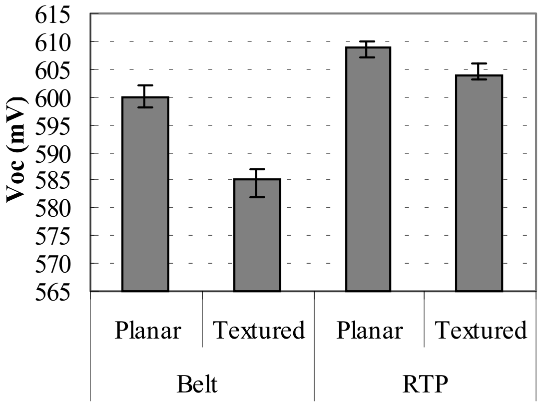


Fig. 1 V_{oc} on different Al-BSF processes. Significant difference of about 15 mV was observed between textured and planar back in case of belt firing Al-BSF. However, firing in RTP reduced this difference to about 5 mV. Ramp-up rate in belt and RTP furnace are 20°C/s and 100°C/s, respectively.

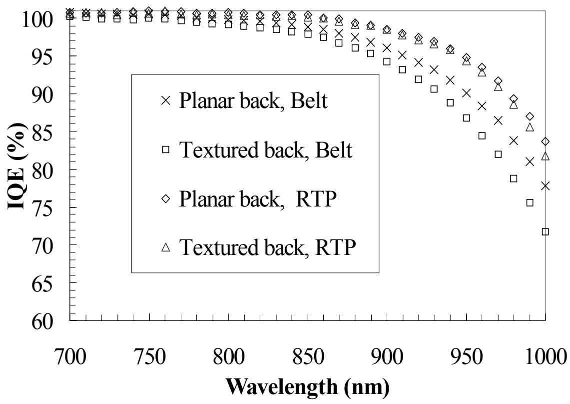


Fig. 2 700-1,000 nm IQE response on different Al-BSF processes. The result is in good agreement with the measured V_{oc} (see Fig. 1). Ramp-up rate in belt and RTP furnace are 20°C/s and 100°C/s, respectively.

in the RTP system reduced this V_{oc} difference to about 5 mV. Fig. 2 shows the IQE response of these cells from 700-1,000 nm. The IQE result is in good agreement with the measured V_{oc}. The data show a better long wavelength response for the planar back cells over the textured back cells in case of belt BSF. However, this difference is very small for the RTP BSF. Consequently, both V_{oc} and IQE results indicate that there is a large difference in the Al-BSF quality between textured and planar back cells when the Al-BSF is formed in the belt furnace, with planar back BSF being superior to textured back BSF. Figs. 1 and 2 also show that RTP not only gives a superior BSF but also reduces the difference between planar and textured back BSF.

A high magnification cross-section SEM picture of an RTP BSF (ramp-up rate of 100°C/s) on a planar surface is shown in Fig. 3 to give an idea of the BSF dimension in this study. Theoritically, only 2 parameters dictate the Al-BSF junction depth : i) as deposited Al thickness and ii) peak alloying temperature. The following expression is widely used for estimating Al-BSF thickness W_{BSF} [4]:

$$W_{BSF} = \frac{t_{Al} \cdot \rho_{Al}}{\rho_{Si}} \left(\frac{F(T)}{1-F(T)} - \frac{F(T_o)}{1-F(T_o)} \right), \quad (1)$$

where t_{Al} represents the as-deposited Al thickness, ρ_{Al} and ρ_{Si} are the density of Al and Si, F(T) is the Si atomic weight percentage of the molten phase at the peak alloying temperature and $F(T_O)$ is the Si atomic weight percentage at the eutectic temperature (constant). F(T) and $F(T_O)$ are obtained from the Al-Si phase diagram.

In this study, an Al paste is screen-printed with a resulting thickness of ~25 µm followed by alloying at 850°C. Using eq. 1, the Al-BSF junction depth is calculated to be ~10 µm. The SEM picture in Fig. 3 shows a BSF thickness of 9-10 µm, which is in good agreement with the calculated thickness.

Figs. 4 and 5 show cross-section SEM pictures of RTP and belt BSF on textured and planar back surfaces. These pictures were captured with significantly lower magnification compared to Fig. 3, since the objective is to

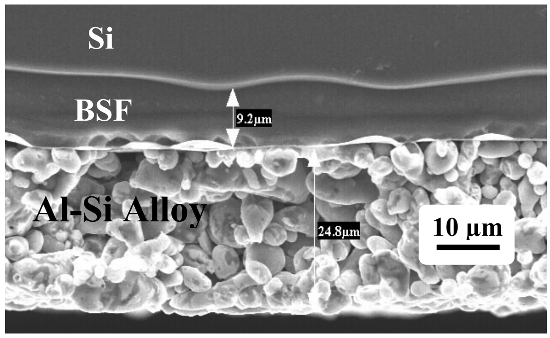
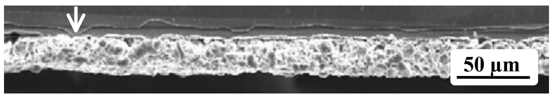
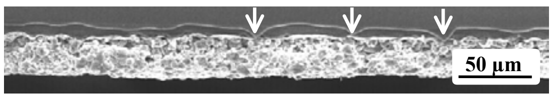


Fig. 3 Cross-section SEM picture of Al-BSF formation for RTP BSF (ramp-up rate of 100°C/s) on a planar back surface.

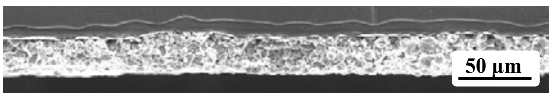


a. Planar surface

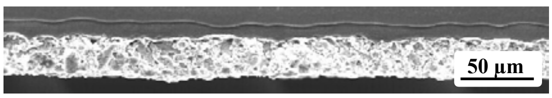


b. Textured surface

Fig. 4 Cross-section SEM picture of Al-BSF formation alloying in belt furnace (ramp-up rate of 20°C/s).



a. Planar surface



b. Textured surface

Fig. 5 Cross-section SEM picture of Al-BSF formation alloying in RTP furnace (ramp-up rate of 100°C/s).

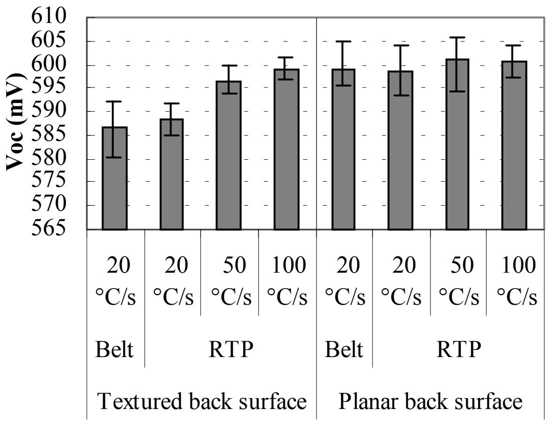


Fig. 6 V_{oc} on different Al-BSF processes. While V_{oc} on texture surface showed strong relation with the ramp-up rate, V_{oc} on planar wafers had negligible dependency. RTP with 20°C/s ramp-up rate showed similar result to that of the belt process.

demonstrate uniformity of the BSF. The images cover 375 μm range along the BSF region. Note that this is a very small section compared to the whole cell, therefore, we carefully chose an appropriate section to represent the whole sample as we scanned through the wide range of BSF cross-section area on each sample. Examination of the SEM pictures in Fig. 4 reveals that the uniformity of BSF on the planar back surface is superior to the textured back surface in the case of Al-alloying in the belt furnace, as indicated by fewer disconnections (marked by arrows in the Figures) observed in the Al-BSF region. However, RTP firing exhibited excellent uniformity on both planar and textured surfaces with no detectable disconnection. The non-uniformity in BSF region lowers the back passivation quality and, therefore, results in higher back surface recombination velocity and lower V_{oc}. We attribute the positive effect of RTP to the much higher temperature ramp-up rate (100°C/s) over slow ramp-up rate in the belt (20°C/s), as described in [5]. In order to gain further insight, we varied the RTP ramp-up rate from 20°C/s to 100°C/s while keeping the same ramp-up rate in the belt furnace (20°C/s).

The V_{oc} of solar cells with different Al alloying ramp-up rates in RTP along with the belt firing are shown in Fig. 6. The data clearly show a better V_{oc} for higher ramp-up rate for textured back samples. The ramp-up rate of 100°C/s gave up to 15 mV higher V_{oc} compared to 20°C/s case. However, small differences in V_{oc} are observed (≤ 5 mV) when the ramp-up rate is varied from 20°C/s to 100°C/s on the planar back cells. The data also show similar V_{oc} values for the belt and RTP BSF cells fabricated with the same ramp-up rate (20°C/s) on both surface types. This result confirms that the dissimilarity in the V_{oc} data between RTP and belt BSF is primarily due to the difference in the ramp-up rate.

Long wavelength IQE responses of all the above cells were also measured and compared (see Figs. 7 and 8). The IQE data is in very good agreement with the measured V_{oc}, revealing better IQE response of cells fabricated with higher ramp-up rate on textured samples. On the other hand, changes in ramp-up rate on planar surfaces did not affect the IQE response significantly. Nevertheless, there is a small difference in the IQE response of cells fabricated with ramp-up rates of 50°C/s and 20°C/s on planar surfaces. This difference is significant in the case of textured samples. IQE data show that ramp-up rate of 50°C/s is fast enough to alloy the Al uniformly on planar surfaces but ramp-up rate as high as 100°C/s may be required to get the best result on textured back cells. It is also seen in the IQE response that RTP and belt fired cells with the same ramp-up rate of 20°C/s gave very similar results on both planar and textured back cases.

In addition to V_{oc} and IQE measurements, uniformity of Al BSF was also examined by SEM analysis of cells fabricated with varying RTP ramp-up rates of 10°C/s, 20°C/s, 50°C/s and 100°C/s (see Figs. 9 and 10). It is clear that the uniformity is better for higher ramp-up rate in both types of surfaces. At the same ramp-up rate, planar samples consistently gave better BSF uniformity than textured samples, except at 100°C/s where both of them showed no disconnection in the BSF region. Interestingly, while 50°C/s showed no discontinuity in BSF on the planar surface, there were still disconnections observed on the textured sample. From these results, it appears that there is a threshold value for ramp-up rate, below which Al-BSF region may be discontinuous. This threshold value is higher for textured than planar back surfaces. This study suggests that the threshold value of ramp-up rate for uniform Al-BSF alloying process is 100°C/s and 50°C/s for textured and planar back surfaces, respectively.

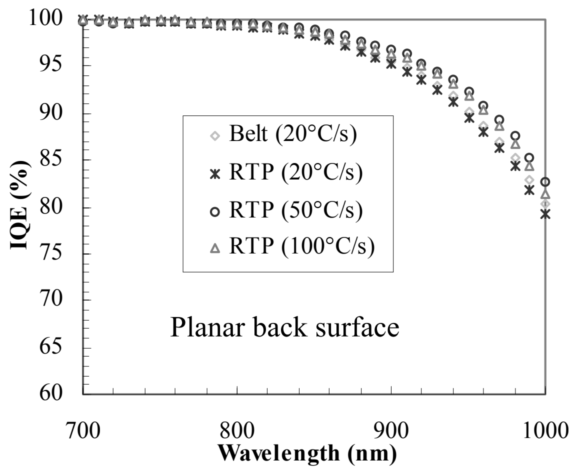


Fig. 7 700-1,000 nm IQE response of planar back cells with different Al-BSF alloying processes.

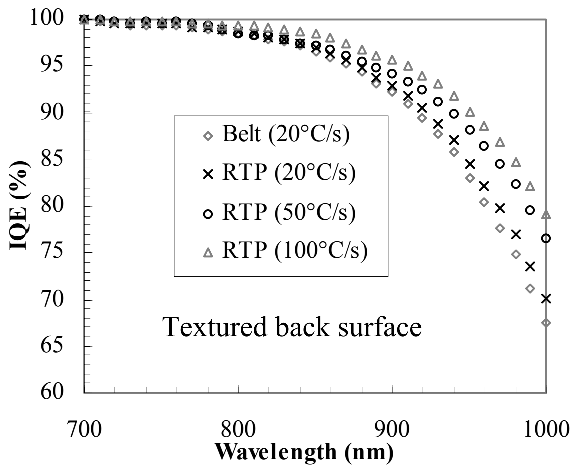
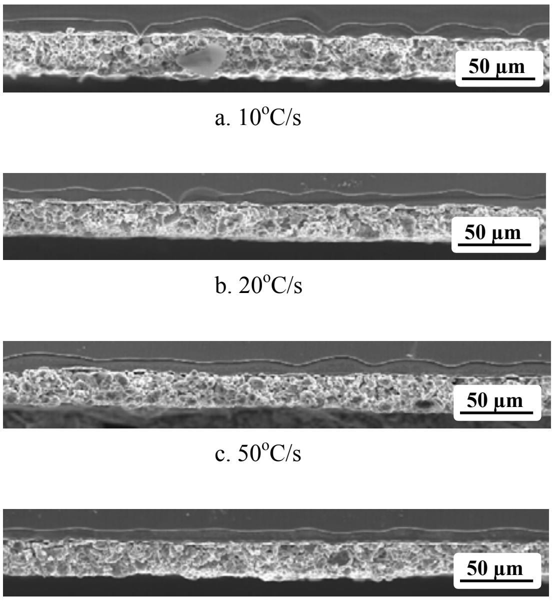


Fig. 8 700-1,000 nm IQE response of textured back cells with different Al-BSF alloying processes.



Planar back surface

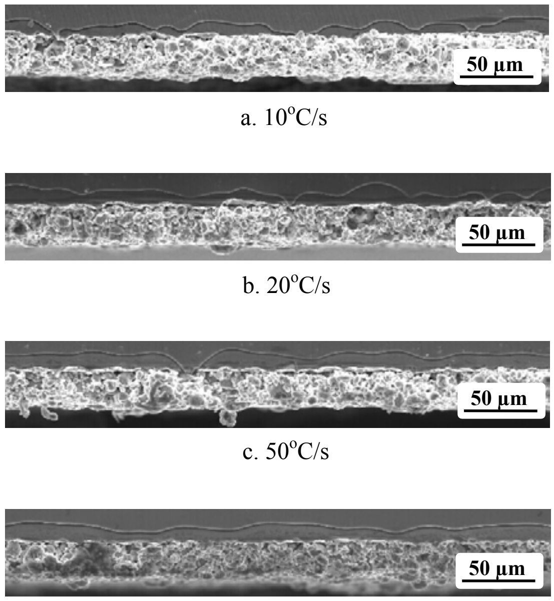
a. 10°C/s

b. 20°C/s

c. 50°C/s

d. 100°C/s

Fig. 9 Cross-section SEM pictures of Al-BSF formation alloying in RTP with varying ramp-up rates on planar back surfaces.



Textured back surface

a. 10°C/s

b. 20°C/s

c. 50°C/s

d. 100°C/s

Fig. 10 Cross-section SEM pictures of Al-BSF formation alloying in RTP with varying ramp-up rates on textured back surfaces.

The positive effect of higher temperature ramp-up rate is due to the fact that it melts the Al more uniformly and quickly resulting in better uniformity of Al-BSF region. This idea was first suggested by [6] in 1968. On the other hand, slow ramp-up rate produces non-uniform BSF even on a planar surface due to non-uniform melting of Al. This effect gets amplified when the surface is rough or textured, resulting in the lowest quality Al-BSF on a textured surface with slowest ramp-up rate of 20°C/s, regardless of furnace type. Thus, if slow Al-alloying process is used on double side textured samples; the positive effect of optical confinement will be compromised by inferior electrical confinement. However, use of fast ramp-up rate process can improve the performance of double-side textured devices by improving both the optical and electrical confinement.

4. CONCLUSIONS

It is shown that the temperature ramp-up rate plays a major role in dictating the uniformity of Al-BSF region formed by Al-Si alloying. Higher ramp-up rate gives better uniformity and therefore, better passivation quality and higher V_{oc}. Slower ramp-up rate during Al alloying gives rise to disconnections in the BSF region, resulting in lower IQE and as much as 15 mV lower V_{oc}. Higher ramp-up rates are required to obtain uniform BSF on textured back surfaces, compared to planar back surfaces. In this study, ramp-up rate of 50°C/s was sufficient to get a uniform BSF on a planar surface but this threshold value was ~100°C/s for the textured back surface. In addition, same ramp-up rate in the belt or RTP furnace gave similar results, suggesting that a very fast belt speed may be able to achieve as good BSF as RTP.

REFERENCES

[1] A. Rohatgi, V. Yelundur, J. Jeong, A. Ristow, M. Hilali, B. Damiani, V. Kumar and P.K. Basu, “Recent Advances and Approach Toward Low-Cost High-Efficiency Multicrystalline Silicon Solar Cells”, *Proc. 11th International Workshop on the Physics of Semiconductor Devices*, (Delhi, 2001) p.73.

[2] P. Lolgen, C. Leguijt, J.A. Eikelboom, R.A. Steeman, W.C. Sinke, L.A. Verhoef, P.F.A. Alkemade and E. Algra, “Aluminum Back-Surface Field Doping Profiles with Surface Recombination Velocities Below 200 cm/s”, *Proc. 23rd PVSC*, (IEEE, Louisville, 1993) p.236.

[3] W.R. Runyan, *Semiconductor Measurements and Instrumentation*, (McGraw-Hill, New York, 1975).

[4] J.D. Alamo, J. Eguren, and A. Luque, “Operating Limits of Al-Alloyed High-Low Junctions for BSF Solar Cells”, *Solid-State Electron* **24**, 415 (1981).

[5] S. Narasimha, *PhD. Thesis*, (Georgia Institute of Technology, 1999).

[6] F.M. Roberts and E.L.G. Wilkinson, “The Controlling Factors in Semiconductor Large Area Alloying Technology”, *Journal of Materials Science* **3**, 110 (1968).

[7] P.A. Basore, “Extended Spectral Analysis of Internal Quantum Efficiency”, *Proc. 23rd PVSC*, (IEEE, Louisville, 1993) p.147.

[8] O. Nast Hartley, R. Russell, K.C. Heasman, N.B. Mason and T.M. Bruton, “Investigation of Thin Aluminium Films on The Rear of Monocrystalline Silicon Solar Cells for Back Surface Field Formation”, *Proc. 29th PVSC*, (IEEE, New Orleans, 2002) p.118.